Computer-supported cooperative work (CSCW)

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Keywords: collaboration, electronic meetings, groupware, team computing, workflow

Abstract

In this article, we consider various definitions for CSCW and related terms, and we draw outlines around the large scope covered by CSCW. Subsequently, we consider the main challenges that have impeded us from realizing the great promise of CSCW and we identify some factors that could help CSCW succeed. We review the current state of practice for CSCW, along with some promising technologies. We close with our outlook for CSCW.

Note: This article combines and updates two articles published in the 2nd edition of the Encyclopedia of Library and Information Sciences published in 2003 by Marcel Dekker. The articles combined and updated were titled: "Computer-Supported Cooperative Work" and "Computer-Supported Cooperative Work Challenges".

Computer-supported cooperative work (CSCW)

Few contest the claim that modern information technology, supported by computers and communications, contributes to a dramatic improvement in productivity and effectiveness among individuals engaged in a wide range of tasks. Computer-supported cooperative work (CSCW) aims to provide similar improvements for “multiple individuals working together in a conscious way in the same production process or in different but related production processes.” (1) If achieved, this aim, which has proven elusive during the relatively few years since the term CSCW was coined in 1984, promises to multiply our productivity, perhaps by more than the square of the number of users, as compared against the productivity improvements that personal computers provide to each of us as individuals.

In this article, we consider various definitions for CSCW and related terms, and we draw outlines around the large scope covered by CSCW. Subsequently, we consider the main challenges that have impeded us from realizing the great promise of CSCW and we identify some factors that could help CSCW succeed. We review the current state of practice for CSCW, along with some promising technologies. We close with our outlook for CSCW.

DEFINITIONS

The term CSCW first appeared in 1984 to identify an interdisciplinary workshop organized by Irene Greif and Paul Cashman at MIT in August of that year for invited researchers to consider how computers might be used more effectively to support people in their various work arrangements. A second, open workshop on CSCW followed in December 1986, attracting 300 people. Since then, an international CSCW workshop (2) has been held every two years, starting in 1988. Because CSCW is such a new area of investigation, one might expect significant controversy and fluidity regarding its definition and focus. Surveys of the CSCW literature support this expectation.

Most observers seem to agree that CSCW, an emerging interdisciplinary field, entails some combination of computing and social science. For example, Greif (3) suggests that CSCW is an interdisciplinary endeavor encompassing artificial intelligence, computer science, psychology, sociology, organizational theory, and anthropology. Similarly, Paul Dourish (4) sees CSCW as a highly diverse discipline involving psychology, sociology, anthropology, network communication, distributed systems, user-interface design, and usability. Beyond agreement on the interdisciplinary nature of CSCW, opinions vary widely about a detailed definition and an exact focus for the field.

CSCW researchers seem to adopt one of two main viewpoints. One viewpoint is technology-centric, placing an emphasis on devising ways to design computer technology to better support people working together. For example, Greif (1) defines CSCW as a distinct and identifiable research field focused on the role of the computer in support of group work. A second viewpoint is work-centric, placing an emphasis on understanding work processes with an aim to better design computer systems so as to support group work. For example, Suchman (5) defines CSCW as “the design of computer-based technologies with explicit concern for the socially organized practices of their intended users.” Similarly, Bannon and Schmidt (6) believe that “CSCW should be conceived as an endeavor to understand the nature of cooperative work as a foundation to designing information systems to support the work.” In a subsequent article, Schmidt and Bannon (7) restate their position, and identify several important questions, listed below, which they believe CSCW researchers must answer.

1. What characteristics distinguish cooperative work from individual work, and what support requirements derive from those characteristics?
2. Why do people work together, and how can computers by applied to address the requirements arising from the specific reasons?
3. How can coordination requirements arising during cooperative work be accomplished more easily using computer technology?
4. What do the identified requirements imply for the development of system architectures and services?

The main emphasis of researchers holding the work-centric viewpoint is to understand cooperative work so as to design computer systems to better support cooperative work. The main emphasis of researchers holding the technology-centric viewpoint is to design computers systems to better support the requirements of cooperative work. Further, as Mahling (8) observes, some social scientists also work in the field of CSCW.

Typically, social scientists working in the field of CSCW aim to describe and analyze the behavior that they see as people work together: focusing purely on description, not prescription. On the other hand, work-centric and technology-centric CSCW researchers aim to create computer systems that address the requirements of cooperative work groups. As such, these researchers hope that the social scientists, through their studies, will prescribe the requirements for successful CSCW systems. To date, this expectation remains unrealized, but much energy has been expended as CSCW researchers work to understand and reconcile these different views. The outlooks suggested by Suchman and by Bannon and Schmidt indicate that some researchers are attempting to work across the gap between description and prescription. In fact, some consensus appears to be building among researchers that CSCW is fundamentally a design-oriented research area. Under this view, the main focus of CSCW should be toward the design of systems that embody a deep understanding of the nature of cooperative work, and its forms and practices. As we will outline in a bit, the current scope of cooperative work, in terms of forms and practices, proves so large that the challenge for CSCW researchers may be overwhelming. First, though, we need to provide some explanation about the many confusing terms and concepts surrounding the field of CSCW.

SELECTED TERMS

Due to its broad scope and relative youth, the field of CSCW encompasses a wide array of specific and sometimes confusing terms. In this section, we introduce and attempt to distinguish among some of the more common terms. People often use *groupware* (9) as a catchy term to refer to CSCW. More specifically, we can think of groupware as computer software and related computer networks that enable collections of people to work cooperatively. Groupware might include application-sharing programs, videoconferencing software, software for tracking document changes, electronic-mail software, and software to support the collaborative viewing of web pages. *Workflow* (10) is another term often used to refer to CSCW. Workflow deals with the specific issues surrounding movement of transactions through a set of people who must act together to complete some required work. In this sense, workflow is a more specific term than groupware; however, workflow software typically supports formal work processes, and so is often excluded from the scope of groupware, which is usually considered to be software that supports less formal forms of collaboration. *Team computing*, a term coined at Xerox PARC (11), refers to collaborative systems to support group meetings. In general, such meetings are envisioned to occur in face-to-face settings. More recently and more conventionally, another term, e*lectronic meetings*, (12) has been used to describe group meetings enhanced through the use of computers, networks, and software. A less common term, *media spaces* (13), occasionally appears in discussions of CSCW. The intent of media spaces is to provide a virtual meeting space where distributed collaborators can congregate electronically, meet informally, and gain all the advantages of collaborators who work together within the same physical location.

KEY DIMENSIONS OF CSCW

As indicated in the brief discussion of definitions and selected terms, CSCW involves a broad, multi-dimensional scope. Here we aim to distinguish some of the important dimensions inherent in CSCW, and to clarify the essential features that must be supported by CSCW systems. Table 1 lists ten key dimensions of the complex design space for CSCW; for each dimension the table indicates two extreme design points. One important dichotomy facing designers of CSCW technology occurs along the *time* dimension: is there a requirement to support cooperative work that occurs simultaneously (synchronously) or separately (asynchronously) or both? Another decision relates to *space*: must the individual collaborators be physically located at the same site, such as a room or an auditorium? Of course, a more complicated requirement might also exist for multiple, physically distant, sites of collocated collaborators to be brought together virtually. A third important dimension is *group size*: must the system support a small team, a department, an enterprise, or a mass audience? A fourth dimension must consider *interaction style*: does the group require support for planned or impromptu interactions or both? A fifth dimension covers *context*: do group members participate in many distinct collaborations or do they tend to participate in only one or few? A sixth dimension relates to *infrastructure*: will the group permit the deployment of homogeneous computing platforms tailored to collaboration or must the CSCW system operate across already deployed, heterogeneous computing systems? A seventh dimension defines *collaborator mobility*: will the collaborators remain at fixed locations or will some or all of the collaborators move among locations? An eighth dimension considers the degree of *privacy*: how much information can be made available about the collaborators and who should control the release of information? A ninth dimension considers *participant selection*: must the group's participants be assigned by existing group members or by some external authority or can participants self-select or search for additional participants from a larger population? A tenth dimension covers *extensibility*: does the CSCW system define the complete functionality available to collaborators or can the collaborators extend the functionality to support changing needs? These ten dimensions provide a rich design space through which the developers of CSCW technology must navigate. Despite such richness, CSCW researchers have been able to focus on some essential features that CSCW systems must provide.

ESSENTIAL FEATURES IN CSCW SYSTEMS

Much of the CSCW research literature focuses on providing collaborators with tools to support *articulation work* (7): establishing and evolving organizational structure, plans and schedules, standard operating procedures, and conceptual schemes for classifying and indexing information objects. In other words, CSCW aims to support the overhead that arises when work is conducted among distributed, independent agents. Articulation work includes two important threads: construction and management of a common, shared information space and workflow management. In the past, designers of workflow systems automated written procedures as maintained by each target organization, which in all cases turned out to be a fictional, idealized version of the real work process. Now, CSCW researchers understand that most work situations entail a continuous renegotiation of task descriptions and allocations. Further, researchers understand that collaborative communication must allow for ambiguity in the negotiation processes surrounding articulation work. To support articulation work, CSCW researchers investigate essential design features in five main areas: communication, configuration, coordination, information access, and interaction. Table 2 indicates some of the specific features encompassed by each of these areas. We discuss these features further below.

COMMUNICATION

Successful negotiation on issues related to organization, planning, and control requires provision of an effective system for communication among the individuals involved. For this reason, human-to-human communication is one of the key features needed for CSCW. Previous research (14) suggests that audio is the most important channel for successful communication. Some CSCW researchers (15-16) have investigated the effectiveness of conference calls, or open-loop multi-party audio channels. Other researchers (17) have shown the value of shared audio channels even when a group of workers is physically collocated. The importance of collaborating around data or documents is also well established. For this reason, a group audio channel is sometimes augmented with a separate distribution channel for sharing views of a document and for highlighting on the document. More sophisticated communication systems integrate audio and data distribution channels together with video channels to compose a form of multimedia conferencing. Whether communicating live (synchronously) or in playback mode (asynchronously), humans can benefit from such multimedia channels.

For live communication, multimedia transmissions often stream data among multiple points in some form of videoconferencing arrangement so that all parties can simultaneously see and hear each other, along with any relevant documents. Satisfactory video viewing usually requires a rate of at least 15 frames per second. Typically, multimedia communication includes an associated audio channel that requires reasonably tight synchronization with the video, within at least 200 milliseconds. These factors place a premium on the quality of service (QoS) provided by the underlying data transmission channels. For this reason, much of the research (18) related to networking for CSCW has investigated techniques to provide the necessary QoS transmission characteristics. Currently, the required QoS can usually be arranged by configuring a conference topology to support multi-party communications at transmission bandwidths (typically ranging up to 2.0 Mbps) provided by H.320-compliant products. Bandwidth requirements for satisfactory multimedia conferencing vary depending upon the configuration of the devices at conference end-points – a minimal conferencing arrangement typically requires around 300 Kbps. Unfortunately, most collaborators must use the more ubiquitous Internet, which does not provide built-in mechanisms to request and achieve specific targets for quality of service. For this reason, much network research (19) related to CSCW has focused on establishing quality of service for multi-party transmissions on the Internet.

In the absence of either multimedia conferencing support or audio communication channels, successful collaboration can still be conducted through the use of text-based interaction systems, known variously as chat (instant-messaging) applications or chat rooms. Text-based chat applications can also provide private channels for a subset of collaborators to hold side conversations outside the purview of the main proceedings. As chat applications become more sophisticated, they can also provide a convenient means to distribute documents, data, and images related to a collaborative session. Beyond free-flowing text-based chat applications, CSCW researchers have developed and assessed a number of techniques for enforcing structure on the dialog and interactions associated with a collaborative session. Such systems, which include news groups, dialog-threading applications, and indexed electronic-mail lists, have proven useful in limited ways. Studies (20-21) have shown that the rather fixed capabilities provided by most of these systems can sometimes impede their effectiveness as a collaboration tool.

Due to the growing role of globalization in the workplace, CSCW researchers have begun to investigate how to facilitate cross-cultural communications, which must bridge differences in natural languages and social norms. Setlock and colleagues (22) investigated the influence of cultural differences among teams, comprising American and Chinese members who work synchronously, either face-to-face or through computers, to solve two tasks. The teams worked in English. The study compares teams, consisting of all Americans, all Chinese and a mix of Americans and Chinese, with respect to several factors (e.g., communication style, quality of interaction, persuasion, and task performance). Yamashita and Ishida (23) considered effects of machine translation on teams, consisting of Chinese, Japanese and Korea members, who worked through instant-messaging software to agree on an ordering of 10 figures. The study compared working with the aid of machine-translation software against collaborating in a common second language (English). The area of cross-cultural and cross-lingual collaboration is due for increased study.

CONFIGURATION

Whether supporting small or large groups, CSCW systems have proven difficult to setup and configure. The scope of such systems is large, covering several layers of system and application software and many points in a distributed topology, both within the network and at network end points. Though relatively few CSCW researchers (24) have chosen to investigate these issues, we suspect that the viability of CSCW systems depends in some large measure on the ease with which collaborative sessions can be established. A number of researchers (25-29) have investigated the difficult problems associated with: (a) extending the capabilities of CSCW systems after deployment, (b) automating adaptation to changes in available resources for transmission and display of data, (c) composing CSCW systems from a range of supporting components, and (d) evolving system components to suit the changing needs of collaborators. Research surrounding the configuration of CSCW systems has not yet received the attention it warrants. Successful adoption of CSCW technology will certainly require an ease of configuration that at least equals and tracks the ease with which desktop computer software can be configured.

COORDINATION

Much of the communication associated with CSCW is used to coordinate work among the disparate, independent parties engaged in a collaborative endeavor. For this reason, CSCW researchers investigate features and mechanisms to help groups coordinate their activities. A major aspect of group coordination involves scheduling, whether of people, processes, or resources. While some CSCW researchers (30) have investigated techniques to more tightly integrate calendaring software with other aspects of collaboration, such as document distribution, situation awareness, and personnel location tracking, more of the research to date has focused on process or workflow scheduling and coordination. For example, Glance, Pagani, and Pareschi (31) investigated process-structure grammars as a means to introduce flexibility into workflow languages. Such grammars describe the relationships among documents and tasks, and use constraints to express soft dependencies, rather than the hard dependencies more often introduced with process-flow languages. Similar goals motivate related research (32) by Paul Dourish and colleagues.

Other researchers (33) focus on mechanisms that permit coordination policies to be established and changed as collaboration unfolds. CSCW researchers should also be interested in techniques for expressing, catching, and handling exceptions during the processing of workflows. The need for such techniques arises because to date implementing workflow procedures has proven brittle. Researchers must also take interest in the issues surrounding delegation of authority and work within a workflow. Such techniques are often used by people in day-to-day work but are usually not supported well in automated workflow systems.

Aside from coordinating direct activities among people, CSCW requires mechanisms to coordinate indirect activities as individuals asynchronously access and updated shared documents, files, objects, and other resources. The needed mechanisms include: control of access and concurrency and maintenance of versioning and consistency. A number of researchers have investigated concurrency control techniques. For example, Prakash (34) has uncovered a range of concerns that arise when providing concurrency control for concurrent editing applications. These concerns include: (a) ensuring adequate response time for shared edit operations, (b) maintaining consistency of results under simultaneous updates, (c) providing adequate capabilities for a per-user "Undo" feature, and (d) ensuring effective awareness of the activities of others engaged in editing the same files. Adopting a formal approach, Ressel and colleagues (35) use a transformation-oriented scheme to represent and reason about concurrency and "Undo" operators, as used within group editors. In a more general look at the relevant issues, Munson (36) and Dewan (37) discuss the larger design space, encompassing a framework for consistency control in synchronous, shared-access applications.

Achieving effective concurrency and consistency control in information sharing applications requires two underlying foundations: access-control policies and versioning policies. Access-control policies establish the ground rules under which various users may access shared information objects. Versioning policies define the ground rules under which different versions of the same object may be combined into a single, consistent copy. In a typical desktop computer, a small set of standard access-control policies is applied to each directory and file that a user creates. Should the user need to extend access to various groups for particular objects, the access-control policies can become quite difficult to establish, understand, and verify. This is one aspect of the problem that faces designers of access-control policies for CSCW. As discussed by Keith Edwards (38) another aspect of this difficult problem is that access-control policies must be changeable during run-time as the requirements of a collaboration change.

While most access-control policies seek to enforce consistency by limiting access to a single user at once, many collaborative activities, such as joint authoring of documents, proceed more efficiently when multiple users can access the same information simultaneously. In such cases, consistency among independent, concurrent updates becomes a key concern. In an attempt to provide an effective system for co-authoring of documents, Rees and colleagues (39) describe a mechanism that separates proposed changes to a shared document space from the orthogonal issues of concurrency control and repository management. Specifically, as a collaborator updates a copy of a shared document, the updates are recorded in change proposals that track information the collaborator expects to revise and that record consistency relationships that must be maintained. Once recorded, change proposals can themselves be treated as shared documents. At an appropriate point, multiple versions of shared documents can be combined and residual inconsistencies can be raised for case-by-case consideration. The area of concurrency and consistency control within multi-user distributed systems remains fertile territory for research, whether applied to CSCW or other relevant applications.

INFORMATION ACCESS

All collaborations require access to information in two classes: subject-matter information and collaboration-support information. Subject-matter information includes the data, images, video clips, spreadsheets, and web pages that contain content related to the subject being discussed in a collaborative session. Collaboration-support information encompasses overhead data, such as session transcripts (which can include all media types: audio, video, text, images, and interaction events) of previous discussions and agreements about plans, procedures, and schedules for the work. CSCW requires the ability to structure, retrieve, distribute, filter, and index information in both classes, whatever the media type. CSCW researchers, as well as researchers in the related fields of information management and digital libraries, work on all of these techniques.

Vannevar Bush (40) provided one of the earliest discussions of automated structuring and retrieval of information when he outlined the possibility of the *memex*, an associative memory enabling the retrieval of information encoded on microfilm, and permitting people to construct an associative web of trails through the information. The ideas behind Bush's memex foreshadowed several later developments, such as the worldwide web, publish-subscribe tuple spaces (41) and globally accessible persistent storage. These later developments (discussed in subsequent sections of this article) seem poised to provide CSCW with a tremendous increase in capabilities to structure and access information. For example, hypertext, a direct descendant of Bush's memex, possesses some significant strengths exploited early on by researchers of web-based systems for collaboration (42-45) and later adopted in several commercial products, such as Netscape Collabra™, WebMeeting™, and eAuditorium™. Unfortunately, as discussed by Jeff Conklin (46), hypertext has two significant drawbacks as an information access technique. First, users often experience disorientation while navigating through hypertext, finding it difficult to identify their current place in the information, such as their route to the current page and routes to return to previous pages. Second, users who structure information as hypertext often report a significant cognitive burden associated with creating, naming, and tracking a large number of hyperlinks. For these reasons, information structuring and access remain important research topics.

Information distribution provides one possible alternative to information retrieval. Information distribution aims to automatically promulgate relevant information to people who might be interested. Such capabilities can be very handy for disseminating information in collaborative sessions. In general, information dissemination systems require some means of description, coupled with mechanisms for matching and delivery. Information subscribers must be able to indicate the characteristics of information they would find interesting and producers must be able to indicate the essential characteristics intrinsic to the information that they create. With these characteristics properly expressed, a computer program can identify matches between subscriber needs and producer data. Once matches are made, distribution can be carried out through a messaging system.

The key issues in information distribution surround description techniques. As discussed by Thomas Malone and colleagues (47), semi-structured messages enable computers to process automatically a much wider range of information than would be possible with free-form text messages alone. In addition, semi-structured messages enable people to communicate non-routine information, which would be impossible within the confines of rigidly structured messages. Malone points out that much of the processing that people already undertake reflects a set of semi-structured messages, so even if no automated processing is anticipated, people can benefit from having an available set of semi-structured message templates to help them formulate messages that contain all relevant information for particular tasks. Further, by adopting a set of semi-structured message templates, automated systems could be adopted and incrementally enhanced more easily over time. Malone and colleagues also illustrate that semi-structured message templates can be arranged in a type hierarchy that can then be supported with a consistent set of display-oriented editors to help people construct messages. Semi-structured messages seem particularly appropriate for collaborative systems because both computers and people can create, read, interpret, and act on the same messages. Semi-structured messages foreshadow the later development of the eXtensible Markup Language (XML), a means to specify computer-interpretable messages that can also be read by people.

While semi-structured messages work well for text data, much of the information associated with collaborative systems exists in the form of image, video, and audio information. Such rich, but unstructured, information presents significant problems with respect to access. The key problems revolve around indexing multimedia information so that people can access it through filters and queries. Some researchers (48) investigate techniques that employ speech-recognition technology to create text transcripts from audio streams. Once an unstructured text database exists, additional technologies can be applied to create multiple indices that identify people, places, dates, and topics included within the data. Using this approach, an audio stream, or repository of audio streams, can be indexed for retrieval or filtering. Some researchers (49) consider audio and video together. Video presents new challenges associated with automatically dividing video clips into scenes or segments. While the audio indexing techniques can help in this process, other techniques can also be applied. For example, if an audio-video stream comes with an associated closed-caption text stream, then information can be extracted directly using topic and subject identification techniques. Other techniques can be applied directly to the video frames in an attempt to identify scene changes. Further, some researchers (50-51) attempt to look inside video frames to identify objects and to extract text, for example on trucks, buildings, and street signs. While analysis and indexing of multimedia streams is typically tackled off-line, some researchers (52) are attempting to perform a rough level of filtering in real-time. The challenging problems surrounding automated indexing of multimedia data continue as targets for active research; however, progress along these lines promises to boost substantially the capabilities of CSCW systems that include video and audio conferencing.

INTERACTION

CSCW must include support for people-to-people interaction at a distance: maintaining awareness of the state and activities of others, managing attention and context when a collaborator becomes involved simultaneously in multiple distinct collaborative sessions, and building and maintaining relationships among people who meet infrequently, if ever. These problems might be among the most difficult that CSCW researchers must address. Still, some progress can be discerned.

An important focus of interaction research deals with awareness at a distance. In order to stimulate ad hoc discussions or to coordinate work, collaborators working in distinct locations must maintain some awareness about the availability and progress of others. This can also extend to awareness about the state of collaborators in multiple, distinct collaborative sessions. The issue is further complicated by the fact that people seem averse to allowing others to peak into their personal space or activities. In a sense, there appears to be a fine line between maintaining awareness and allowing unwanted intrusions. Hudson and Smith (53) have considered associated tradeoffs. Several researchers (54-55) investigate video-based techniques that can reduce the problem of intrusiveness, while simultaneously facilitating ad hoc interactions among distributed groups. Nomura and colleagues (56) experiment with techniques to provide peripheral awareness through shared workspaces. Others (57-59) propose mechanisms to provide awareness within the context of application sharing and groupware systems. Some researchers (60) even imagine that desktop computers can be used successfully for impromptu interactions. Taking a less constrained view, Tollmar and colleagues (61) have designed and experimented with several techniques intended to enhance social awareness within the work place. Awareness in CSCW systems remains an important and fertile area for research.

Another difficult challenge for CSCW researchers involves development of techniques to effectively manage the attention of collaborators, especially when individuals may become involved in multiple, but separate, collaborative sessions at the same time. Belotti and Bly (62) examined the problem of context management in an environment where people move among physical locations to engage in various collaborations. Fitzpatrick and her colleagues (63) studied the problem for virtual collaborations; specifically, they investigated the issues that arose as a group of system administrators collaborated remotely with each other and with system users to identify and solve problems with the configuration of computer systems. Results from the study influenced the design of Orbit (64), a research system to support desktop collaboration where the user engages simultaneously in multiple collaborative contexts. Other researchers attempt to solve the problem of context management through the use of various metaphors, such as “virtual places” and “virtual spaces” (65) and “team rooms” (66). Even in a physical workspace, many people find it difficult to manage multiple working contexts, as well as to manage their own time and attention. Computer systems bring the possibility for people to engage in many more activities at once. Aiding people to effectively manage these more numerous contexts remains a challenging research issue.

CSCW researchers must also address a subtler problem: how can people find appropriate collaborators and then build and maintain effective relationships without much physical contact? These issues will become increasingly important as business interactions move more and more to the digital realm, which can reduce the inconvenience, cost, and other inefficiencies associated with physical travel to face-to-face meetings. One typical problem confronting people, even within the same organization, is to find appropriate experts to answer a specific question or problem, or to apply a particular body of knowledge. For this reason, several researchers (67-69) have investigated systems to facilitate finding knowledge and expertise through a social network. Other researchers (70-72) have explored the use of collaborative filtering systems, which do not necessarily include information about the expertise of the participants but which can be applied on a large scale, such as the World Wide Web (the Web). Since the Web encompasses millions of users, some researchers attempt to leverage typical behaviors among Web users to help connect them to possible collaborators without incurring additional cognitive overhead. For example, Payton and colleagues (73) devised a novel way for people to discover potential collaborators based on comparisons among individual patterns of web browsing, which are typically logged by a computer. After converting logs of web accesses into graphs associated with each user, a matching program can measure similarities and differences and then bring people into contact through electronic mail. Included within this research are several mechanisms intended to protect individual privacy, a concern that might be raised by potential users when a computer system is applied to passively monitor their activities. Even in some face-to-face situations, such as large conferences or meetings, electronic systems can be used to help stimulate new collaborations. For example, Borovoy and colleagues (74) developed "Meme Tags", wearable devices with displays that enable conference attendees to electronically share succinct ideas or opinions. Based on the shared information, conference attendees could form into groups with similar interests. Behind the scenes, a server system monitors and collects information about tag exchanges and then reflects the information back to conference attendees in "Community Mirrors", which are publicly visible displays that present real-time views of the unfolding dynamics within a community. Similar ideas have been used within cyberspace to permit groups of individuals with related interests to form and interact from among millions of undifferentiated participants. Usenet (75), pioneered in 1979 by Jim Ellis, provides one of the earliest examples. Usenet enables the creation of newsgroups focused on particular topics. Individual users can discover the existence of such groups, subscribe to those of interest, and then participate in asynchronous conversations through threaded, text postings. The more popular newsgroups sustain interactions among hundreds or thousands of users. Newsgroups continued in popularity as tens of millions of users moved onto the Internet during the 1990's. In fact, newsgroups have helped to form the ocean of Internet users into smaller collections of folks with similar interests. From these smaller collections, some individuals form and sustain deeper connections, a human art which can require additional assistance in the digital domain.

Establishing, developing, and maintaining human relationships typically relies on (13): (a) informal social contact, (b) chance encounters in hallways, (c) chats before and after formal meetings, (d) discovery of shared interests, (e) feelings of community, and (f) implicit knowledge of the state of others. While many of these factors occur naturally among collocated people, some researchers (76) have observed that social responsibility and commitment appear to diminish when people do not meet face-to-face. For this reason, CSCW researchers often attempt to recreate these relationship-building factors when people must interact at a distance. We have surveyed much of the relevant research already. A few CSCW researchers (77-78) have focused specifically on building relationships with significant depth and trust while working at a distance. Research surrounding these topics will increase in importance as work becomes more reliant on digital interaction at a distance.

CSCW CHALLENGES

To derive the greatest benefit from CSCW, the supporting technology must infiltrate as widely as possible throughout the populace. CSCW researchers have conducted studies that support this assertion. For example, Steve Whittaker (79), in a study of users of Lotus Notes, a technology intended to support asynchronous collaboration, found that both conversations and the creation of group archives proved more successful with large numbers of diverse participants, as compared against small, more homogeneous, project teams. Similarly, Whittaker reports that a large database of material was more likely to be used and extended than a small database. Further, the presence of a moderator was found to inhibit rather than enhance discussions. In other words, Whittaker's study suggests that the larger and more diverse the population of participants and the more free-flowing the conversations, the more effective the results.

What factors inhibit the widespread adoption of CSCW technology? First, CSCW technology generally relies on a big stack of computer and network technology, operating systems and protocols, data formats and user-interface devices. The dissemination of such capabilities, while growing at a rapid pace, is far from ubiquitous, and even where these technologies have penetrated, the systems, protocols, formats, and software is far from homogeneous. We can safely observe that the telephone handset appears to be ubiquitous, while the networked desktop computer is far less so. Some progress can be discerned regarding de facto standardization of desktop computer systems and software, as well as the adoption of standards associated with the World Wide Web. Even so, these technical underpinnings on which CSCW depends continue to evolve. Further, there exists little penetration of the systems, and associated networking quality of service required, to support effective videoconferencing. These facts suggest that to some large degree the pace of progress in CSCW depends upon, and must be tied directly to, those supporting technologies that achieve near ubiquitous adoption. On the other hand, as selected technologies evolve over time to become ubiquitous, the degrees of freedom available to CSCW researchers and designers also diminish.

Even assuming that the necessary networking and computing technologies achieve complete penetration throughout society, the deployment of CSCW may still be retarded by various administrative and policy decisions, which paradoxically may in part be taken in reaction to the depth of penetration of the technologies themselves. For example, as more people gain access to the Internet the potential increases for various unwanted intrusions, eavesdropping, information theft, and denial-of-service attacks. To limit the effects of such incursions, network managers have deployed security firewalls. Such firewalls are typically configured to impede the free flow of communication among nodes on the Internet. These restrictions attempt to turn a physically ubiquitous system of nodes into logically partitioned and protected enclaves of nodes, and thus interfere with the ability of people to collaborate – especially when the potential collaborators exist within separate administrative domains.

Beyond the need for widespread adoption of the necessary underlying technology, CSCW can suffer from Grudin's inequality (20), which states: those who devote the time and effort to capture and record the articulation work associated with collaboration, may not be the ones who benefit most from the results. This same issue appears again, but on a larger scale associated with knowledge management, in a panel discussion held at the 1998 conference on CSCW, where participants considered the question: "can an organization shape its culture so that people will network and share expertise, making knowledge explicit whenever possible, rather than just whenever convenient?" In this case, an entire organization stands to benefit from the time invested by its individual members, while the members themselves might not gain directly from the time they invest.

Another impediment to progress in CSCW concerns a general inability to measure progress within the field. In hardware-related fields progress can be measured easily along many relevant dimensions, such as component density, execution speed, power consumption, and heat dissipation. To date progress in software-related fields has proven less amenable to quantification. A compounding factor, identified by Whittaker (79), is that user perceptions about the effectiveness of CSCW technology often do not match the effectiveness as measured by an unbiased, outside observer. This finding implies that measuring progress in the field of CSCW cannot rely solely on surveying the experiences of users. For this reason, large companies often spend substantial resources to set up human-factors laboratories where users can be observed and recorded while using specific technologies and where the observations and recordings can be studied to glean information about the effectiveness and efficiency of various software features. Understandably, because CSCW encompasses a complex and multifaceted research domain, measuring progress will remain difficult. Some researchers (81) have proposed a framework intended to encompass the important dimensions along which progress can be measured, and to provide some examples (82-83) showing how to apply the framework.

While conducting research and measuring progress in CSCW appears challenging enough, we must also consider the fact that the underlying technology on which CSCW builds continues to change at an alarming rate. Because CSCW builds on a wide range of software and networking technologies, significant advances in those fields can challenge the assumptions on which CSCW applications are constructed. In fact, CSCW applications live at the end of a long food chain of technologies, and so must adapt to any changes that arise. Further, several technologies within the food chain can change simultaneously, making it difficult for CSCW researchers and developers to track and understand the significance of the changes, let alone adapt to them. Even if CSCW researchers could adapt fast enough to technological changes, there still remains the problem of understanding and evaluating the effectiveness of the adaptations. By the time researchers gain an understanding, the underlying technologies have typically moved on again. This cycle poses quite a challenge to CSCW. Even worse, the adoption of new technologies and CSCW applications by people and organizations inevitably leads to changes in the way people work, as well as in the assumptions that people make about what should be possible or expected from CSCW in any given circumstance. For example, Olson and Teasley (76) discuss how working arrangements among a team changed to become more loosely coupled when the team was forced to work virtually at a distance. Similarly, Malone (84) predicts a shift in the organizational structure of corporations as they come to depend on computer-mediated coordination technologies. This co-evolution between CSCW technology and the reaction of people and organizations to the technology appears even more challenging when we consider the fact that evolution along each dimension operates on different timescales. While technology evolves quickly, people and organizations tend to resist change, or to change fairly slowly, perhaps even at a generational pace. This mismatch in the pace of change adds to the difficulty CSCW researchers face when they attempt to assess progress in the field.

CSCW SUCCESS FACTORS

Given the challenges facing the field of CSCW, can we identify some keys to success? First, success depends on the degree to which CSCW technology becomes ubiquitously deployed throughout society. This implies that CSCW researchers must target their innovations and developments to ride on underlying technologies that appear poised for widespread adoption by a substantial portion of the population. Past examples of such technologies include telephones (in 1999 the Federal Communications Commission estimated that about 94 % of Americans had telephones) and televisions (Nielsen Media Research-NTI reported that sometime between 1980 and 1985, televisions penetrated 98 % of U.S. households). Potential future examples include the World Wide Web, which connects millions of desktop computers together, and to information and communication services. To date, World Wide Web technology has penetrated to between 50 % and 70 % of the population in industrialized nations, depending on the specific country, as reported in a study, “Truly a World Wide Web – Globe Going Digital”, conducted by the Pew Global Attitudes project, released in May 2006. That study reported that the percentage of Americans with on-line access increased from about 64 % in 2002 to 70 % in 2005, while Internet usage by the world's two most populous countries lags: only 38 % of Chinese and 14 % of Indians used the Internet in 2005. While not certain, desktop computers and the Web seem likely candidates for near ubiquitous deployment.

Second, CSCW researchers must focus their efforts to understand and account for the characteristics of cooperative work. Some researchers have already contributed in this way. For example, Ehrlich (9) reports themes from research about group work. Communication among groups is generally ad hoc, informal, and unplanned, which implies that CSCW researchers should develop techniques that can support such interactions in the digital world. Group members also need to maintain awareness about the availability of others to communicate, and about the state of joint work, which implies that CSCW researchers should seek to improve our ability to accomplish these tasks when working through computers and across networks. Further, issues related to sharing information often hinge on subtle notions of anonymity, which suggests the CSCW researchers should continue to experiment with mechanisms to manage the release of personal information in cooperative settings. In another contribution, Schmidt and Bannon (7) suggest some guidelines to consider when designing systems to support cooperative ensembles. Cooperative ensembles: (a) exist as large assemblies or as groups embedded within larger assemblies (which implies that CSCW researchers should focus on techniques that scale); (b) often emerge to handle a particular situation, then dissolve (which implies that CSCW researchers should explore techniques that ease the burden of establishing collaborative sessions); (c) exhibit continuously changing membership, or membership that cannot be determined (which implies the CSCW researchers should investigate techniques for finding and forming effective subsets from larger populations); (d) often intersect (which implies that CSCW researchers should develop techniques to manage multiple collaborative contexts, including mechanisms to control the dissemination of information in accordance with policies that might conflict). MacKay (13) highlights another key to success when she identifies the importance of mechanisms that enable people to control who can see or hear them at any time, and to know when someone is seeing or hearing them. MacKay also discusses a critical issue surrounding interaction and interruption. Specifically, individuals desire to determine the intention of any proposed connection or interaction, and to avoid communications that might disturb their work. These observations imply that CSCW researchers could focus productively on mechanisms to automate the initiation and management of interactions.

A third key to success for CSCW relates to automated support for coordinating group activities. While CSCW researchers are now convinced that most workflow and coordination processes demand continuous negotiation among participants and entail liberal application of techniques to handle unanticipated exceptions, the work of coordination remains largely a domain where only people add value. While selected CSCW researchers investigate automated, language-based support for flexible workflow processes and for negotiation and coordination, this territory remains wide open. Will agent-based coordination systems really work effectively? Can constraint-based languages be applied to achieve flexible information and transaction flow? Can automated methods support coordination among people, or are the problems too hard? Finding the right balance between automated support and human responsibility could improve the prospects for CSCW technology to go beyond communication to include coordination.

CURRENT PRACTICE OF CSCW

While some technologies appear promising as foundations for advances in CSCW, it should prove instructive to consider the current state of the practice. The typical collaborative session today consists of a telephone conference where collaborators discuss content, which might include faxed documents or perhaps some shared electronic documents, such as presentation slides or word-processing files that might be supported by change tracking capabilities. In some advanced situations, a collaborative activity that extends beyond particular real-time sessions might also be supported by a web site, with one person elected as the editor. Usually, files to be added to the web site would be sent by electronic mail to the editor. This typical collaborative session leverages a ubiquitous technology, the telephone network, which also happens to provide one of the most important channels, audio, for quickly conveying information among people and for conducting the real-time interactive dialog that helps to coordinate understanding and consensus building among participants. Typical collaborative sessions might also exploit the telephone network to distribute paper documents through facsimile machines. This permits discussions to center around shared documents, but relies on the use of the audio channel to ensure that all participants focus their attention on the same locations within a document. Increasingly, electronic mail is replacing the facsimile as a mechanism to distribute documents, and the documents usually adopt a widely available format, such as Adobe portable document format or Microsoft Word™ format, which also provides change-tracking capability, along with PowerPoint™ format for shared viewgraphs. These techniques help, particularly the change-tracking capability, which can be useful when several people wish to propose amendments to shared documents. Even in this case, either the document must be distributed serially to ensure all changes are recorded, or the collaborators are left to ponder changes independently proposed on various copies of the document. No clear advantage exists for either approach because it can be somewhat difficult to follow documents marked up with proposed changes. Notice that the use of electronic mail to distribute electronic documents still relies on the audio channel to coordinate the focus and attention of all participants during a collaborative session.

Some technologies aimed at improving the state of the practice have failed as yet to provide much help. For example, application-sharing systems exist (e.g., Microsoft's NetMeeting™) that provide a means to visually indicate focus on electronic documents, that support simultaneous markup of electronic documents among a group of users, and that also include audio and video conferencing capabilities. Yet, these systems are not in widespread use. Why? Few widely agreed standards exist. The systems prove difficult to configure and use. They require support for a level of network quality of service that is not widely available. Videoconferencing systems, such as the roll-around stations and room-based systems available from PictureTel and Polycom, have failed to achieve ubiquity as well. Why? Such systems tend to be expensive; thus, they are deployed selectively and must be scheduled and shared. This limits their applicability for spontaneous collaboration. Further, such systems require specialized support for network quality of service, usually provided through H.320-compliant dial-up lines. The Internet, while more widely deployed, does not provide the necessary support for guaranteed quality of service. Systems (such as Lotus Notes) that support asynchronous collaboration can be used to disseminate documents and discussions and to trigger alerts when various events occur. Such systems have not achieved wide usage. Why? The litany of reasons should be familiar by now: lack of widely agreed standards; difficult to configure, deploy, and use; expensive to buy and maintain. A similar story can be told for collaboration servers, such as Collabra and TeamWare, another form of collaboration technology available today, but not widely used.

While the current state of the practice in CSCW appears rather primitive and the landscape of more advanced technical solutions appears strewn with failures, some technologies promise to better support CSCW in practice. For example, the Web, with a growing infiltration in society and an increasing base of widely agreed technical standards, looms as a mass medium that can likely be exploited for collaborative purposes. In fact, as the Web's inventor, Tim Berners-Lee, has often observed (85), collaborative software development provided the original motivation behind the Web. Of course, Mr. Berners-Lee has also rued the fact that at its current state of development the Web appears to be a mass medium more suited for TV-like distribution of multimedia. Despite its current state, Mr. Berners-Lee and many other researchers (86) and developers continue to seek mechanisms to improve the Web's support for collaboration. Great potential exists for CSCW on the Web because ubiquitous availability provides a crucial key to success.

Another significant development for CSCW appears to be the growing role of distributed, collaborative software development, as fostered by the "Open Source" movement (87). Of particular interest is SourceForge (http://www.sourceforge.net), a Web site that provides services to open-source software development projects distributed around the globe. SourceForge provides hosted projects with Web-based tools for collaborative software development, a project Web server, tools for software maintenance and bug tracking, mailing lists and discussion forums, databases and compile farms, software release services, and advertising. SourceForge users have the option to mix-and-match these tools, and are free to design and contribute tools that might enhance collaboration. As of May 2007, SourceForge hosted over 150,000 open-source development projects and more than 1.6 million registered users. These figures represent a five-fold increase in the past five years. We might conclude that SourceForge employs

Web technology in a form intended to realize the original motivation cited by Mr. Berners-Lee: collaborative software development.

What can we conclude from our examination of the current state of the practice in CSCW? The successful CSCW technologies appear to share some traits: ubiquitously available, easy to understand, easy to set up and use, few administrative constraints, reasonable technical requirements, and affordable prices. The unsuccessful CSCW technologies fail with respect to one or more of these traits. The expansion of users on the Web seems likely to continue, perhaps achieving near ubiquity at some future date. Such ubiquity would provide a key foundation to improve computer-mediated collaboration at a distance. SourceForge provides an early glimpse of what might become possible. While current practice appears quite limited, growth in Internet-based communication suggests that we are living near the dawn of effective CSCW. A number of technologies seem particularly promising.

PROMISING CSCW TECHNOLOGIES

If we look a bit beyond the horizon of today's widely deployed systems, we can identify a few technologies that exhibit significant promise with regard to CSCW. One suite of technologies might enable us to divide the general Internet up into virtual communities inside which we can securely conduct collaborative sessions, both in real-time and across time. Such technologies can replace the current firewalls, which divide the Internet up along administrative boundaries, with virtual enclaves, which might divide the Internet up, on demand, along the lines of function or context. Already elements of such technologies are commercially available. For example, Microsoft Windows™ ships with networking technology that enables users to form virtual private networks, which use encryption to establish confidential, virtual Internets on top of the physical Internet. Other commercial products, such as VMware™ and the XenServer™, permit a single desktop computer to be divided into virtual operating systems, which provide multiple, separate contexts for users or to divide web servers into segregated enclaves so that a single physical web server can appear as multiple, logically distinct web servers. Desktop, network, web server – these assets form the ingredients needed to support collaborative sessions among distributed users across organizations, and the ability to "virtualize" each of these assets in order to support multiple but separate contexts already exists in the commercial market. What remains to be developed are: (a) techniques for connecting these distinct virtual assets into unified virtual enclaves, each consisting of virtual desktops, a virtual network, and virtual servers, and (b) mechanisms to quickly establish virtual enclaves and to support mobility among the virtual desktops and virtual servers. Some networking researchers (88) have already investigated techniques for composing virtual enclaves, while other networking researchers (89) have refined technology that can allow virtual networks to be established simply and on demand. Recent research (90) promises to deliver on-demand allocation of optical communications paths, which should support virtual networks and provide sufficient quality of service to support a wide-range of multimedia channels to support collaboration. At the forefront of current research, grid software available as part of the Globus software distribution (91) is being developed to allow collaborators from multiple administrative domains to contribute resources into a virtual organization hidden from unauthorized members.

Above the networking and operating system layers, technologies for the Web are evolving in interesting ways that also promise to support improved CSCW. We previously mentioned the advantage of the eXtensible Markup Language (XML) for describing the syntax and content of information in a form both readable by people and interpretable by computers. XML (92) seems likely to become the standard language for defining information objects exchanged among computers. Future evolutions of XML (86) promise to annotate information objects with semantic tags that can enable intelligent interpretation on the part of supporting software applications. CSCW researchers and developers should be able to build safely on this base. Early examples of what might be possible exist in the form of community-based Web sites, such as MySpace (with its 182 million users) and Facebook (which has 23 million members), and Web sites aimed at establishing and extending business networks, such as LinkedIn (11 million users).

XML does not include a means to describe the behavior associated with various objects, except in the form of references to programs that can implement services associated with the object. The ability to express behavior directly in a form that can be transferred between computers seems to have an important place in future automated systems. At present, candidates for this role include portable scripting languages, such as Python, RubyScript, TclScript, and network programming languages, such as C# and Java™. Some researchers (27) have used Java to implement Habanero, a combined synchronous-asynchronous collaborative system that shows how the power of mobile programs can be applied to bring unprecedented interoperability, function, and performance to CSCW.

While XML and Java™ suggest how meta-data and behavior can be described for dissemination among a network of computers, other technologies promise to provide new mechanisms to accomplish the distribution. Already, industry is busy working on notification services and publish-subscribe (pub-sub) technology that will facilitate the distribution of events and notifications to all people who have an interest. These pub-sub technologies, such as Web-Services Notification and JXTA™, build on research conducted by David Gelertner (41), who investigated the applicability of "tuple spaces" as a means for efficient, large-scale coordination among many distributed processes.
Gelertner, a creative and visionary computer scientist, also investigates (93) techniques for organizing multimedia experiences, so-called lifestreams, into a readily accessible form. Such technology would serve admirably to enhance the ability of collaborators to locate relevant information. Earlier, we discussed other research along these lines, such as Rough'n'Ready (48) and Informedia (49), when we considered the importance of access to raw multimedia recordings of collaborative sessions. While this class of research has not yet matured to the point of widespread commercial availability, CSCW developers should be poised to make effective use of the technology.

As outlined earlier, existing technology for videoconferencing has failed to achieve widespread acceptance, probably due to expense, configuration complexity, and requirements for guaranteed quality of service from the network. Despite the seeming failure of this technology, some researchers continue to investigate the possibility for radical advancements in multimedia conferencing. For example, Jaron Lanier (94) advocates tele-immersion, a technology that aims to facilitate live multimedia interaction. The goal of Lanier and colleagues is to exploit computers, sensors, display technology, and networks to enable remotely distributed collaborators to hold virtual meetings with the same degree of quality as if they were collocated. Similarly, Rick Stephens and colleagues (95) have developed software to integrate large numbers of multimedia devices with high-speed networking channels to provide various sizes of Access Grid, aimed at enhancing remote collaboration across administrative domains. Success along these lines would prove invaluable to enhance the power and effectiveness of CSCW.

Not to be overlooked is research intended to exploit and enhance familiar modes of interaction as a basis to support human collaboration. For example, Paul Luff and colleagues (96) are devising techniques that enable paper to become an input device for selecting functions, and fulfilling roles now played by computer mouse devices and graphics tablets. As another example, technology for creating digital paper (97) and thin, flexible displays (98) promises to enable the use of paper-like devices to load and exhibit information, which could provide significant improvements over current forms of visualization, freeing mobile collaborators from reliance on bulky, expensive, power-hungry displays. Companies (such as E Ink and Universal Display Corporation) are already developing some products along these lines. More work will be required to integrate paper-based input modalities along with digital paper or flexible displays in order to provide mobile collaborators with the ability to interact conveniently while consuming little power. CSCW developers and researchers would be well advised to increase their investigation of techniques that can exploit familiar human interaction devices, such as whiteboards, walls, tape, paper pads, markers, and pens, while simultaneously crossing the boundary between the physical and digital worlds. Examples of promising lines of research include the Easy Living (99) and Sentient Computing (100) projects, the Mixed Reality Architecture (101) and Microsoft’s ‘Surface’ (102) interactive table. Finding effective methods to bridge the gap between people and computers promises to yield great improvement in the interaction of groups.

OUTLOOK FOR CSCW

CSCW has become a hot technology and seems likely to remain so for the foreseeable future. The information age, and related exigencies associated with increasing globalization and specialization in our modern society, impels an ongoing transformation in the organization of work. Work is becoming more information-based, relying on computers and communications, and increasingly involves the activities of teams, often across organizational boundaries and time zones. Usually, people work on multiple teams, where the team composition changes depending upon the context, subject, and business arrangements. In this demanding environment, organizations and people naturally seek to employ any technology that can help get the job done better, faster, cheaper. These factors presage difficult, long-term problems whose solutions hold immense potential to benefit companies, individuals, nations, and society. Today we stand only 25 years into what might be a 50-year endeavor to research, develop, deploy, and refine effective, efficient and affordable technology for CSCW. CSCW might encompass the greatest challenges facing information technology researchers and developers, but CSCW also promises to deliver the greatest benefits that computer, network, and software technologies have to offer mankind. The central question guiding the CSCW field can be stated simply. How can computing systems enhance cooperative work without unduly constraining human collaborative processes? The question has no simple answer.

Table 1. Ten Key Dimensions in the CSCW Design Space

Dimension	**Extreme Design Points**
Time	Fully Simultaneous vs. Fully Disjoint
Space	All Collocated vs. Fully Distributed Participants
Group Size	Small Team vs. Mass Audience
Interaction Style	Assigned Workflow vs. Ad Hoc
Context	Single vs. Unlimited Collaborations Per Participant
Infrastructure	Fully Homogeneous vs. Fully Heterogeneous
Collaborator Mobility	All in Fixed Locations vs. All Mobile
Privacy	Assigned by Authority vs. Controlled by Participant
Participant Selection	Assigned by Authority vs. Free for All
Extensibility	None vs. All Functionality Defined by Participants

Table 2. Five CSCW Design Areas and Some Key Design Features in Each

Design Area	Key Features
Communication	Asynchronous, Audio, Data, Private, Shared, Structured, Synchronous, Text, Unstructured, Video
Configuration	Adaptation, Composition, Evolution, Extension
Coordination	Access Control, Concurrency, Consistency, Delegation, Scheduling, Versioning
Information Access	Distribution, Filtering, Retrieval, Structure
Interaction	Attention Management, Awareness, Context Management, Relationship Establishment and Maintenance

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